NUMERICAL, EXPERIMENTAL AND ANALYTICAL INVESTIGATION

FOR HIGHER WIND TURBINE EFFICIENCY

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ABSTRACT

The study is based on Energy Possessed by the running rotors. Explained with Analytical Reasons and worked with Numerical Fluid Mechanics calculations for both useful energy produced and energy wasted by the running model rotors are also presented. The experimental work is carried out for nine Horizontal Axis wind rotors and one Vertical axis wind rotor physical models. By Changing the Wind Turbine Rotor Geometry and analyzing their theoretical and actual performance for a possible higher efficiency of energy extraction from the moving air. Between speed and power of the wind rotor an optimum size and angle are to be kept for each of the blades to harness the possible maximum kinetic energy from the wind is the deduction from the results as otherwise wastage of energy is higher. Energy is an imported input in many sectors of any country's economy. Present Position: 1. Population of world has increased 2. Standard of living of human beings has also increased and so the per capita energy consumption has increased. A wind turbine is a rotating machine and looks like a big fan that converts the kinetic energy of wind into useful mechanical energy. This Mechanical kinetic energy can be used directly by any machinery such as a Water pump, Wood cutter or for grinding food grains. Such a machine is called a wind mill which is a very old device historically. If in a wind turbine the mechanical energy produced is instead converted into electricity then it is a wind generator, wind turbine, wind power unit (WPU), wind energy converter (WEC) and so on the names which also extracts energy from moving air by slowing down the speed of the wind, absorbing and transferring this harvested mechanical kinetic energy of the moving air into a rotating shaft which usually turns an alternator or generator to produce electricity.

Wind turbines are by and large (a) Horizontal Axis (b) Vertical Axis Types. The Present experimental study the results are showing significant improvement for the horizontal axis type wind turbines which are more efficient than the vertical axis type of wind turbines. A conclusion is that an increasingly larger size of the blades from the inner to the outer periphery with appropriate angle of the blade is able to produce more energy output from the same moving air. With an increased efficiency one particular rotor is able to run and produce higher energy output. From a constant air flow source and by placing each of the model rotors in front of the blowing air the rotors are allowed to rotate and tested. The rotors are so designed and made to have various Solidity ratio, Blade angle, Tip Speed ratio and Mass. Different Energy possessed by each of them while running and efficiency of each of the ten rotors are calculated numerically and experimentally. The energy equation is used and the maximum rotational speed of the rotors under identical conditions are measured using noncontact type optical sensor. About 30 to 40 % more energy efficient is the case for particular rotor geometry is reported and recorded for the first time which can be due to better engineering design. Since the experimental test results also firmly supports the above final conclusion it is recommended that Commercial wind turbine manufacturers can confidently change the existing wind turbine rotor blade design from the smaller tip at the outer end of each blade into a larger tip. The

increase in efficiency can be analytically justified to the higher torque produced and hence the more energy extraction by the larger tip area of the blades.

KEYWORDS

Wind Turbine, Horizontal axis wind Turbine, Wind speed, Wind power availability, Cut in speed of wind turbine, Torque developed by the wind turbine, Swept area of the blades, Tip area of the blades, Energy possessed by the running wind Turbines, Cause and reasons for actual Improved Efficiency of energy conversion.

INTRODUCTION

Present Energy Need

Wind energy is a non polluting source of energy. Now the condition is there is always a need for electricity and to have electricity produced either by burning of fossil fuels with lower level of exhaust gas pollution or by producing and using more effective devices may be say a better performing wind turbines which will not have any pollution but at the same time generate electrical energy at a lower cost. Now an attempt is being made to carry out to the extent possible Existing Horizontal Axis Wind Turbine Blades altered to produce some more energy from the same input energy. The important point is wind energy is perennial and everlasting.

To the extent possible a Comprehensive Experimental and Numerical investigations with physical models of wind rotors is made.

- Human Population of world has increased many fold 2. Standard of living for human beings has increased a lot. Per capita energy consumption 8000KWh in some country and 150KWh in some other country. A country with 7% of world's population consumes 32% of total energy consumed the world. Whereas in another country which has 20% of world's population consumes only 1% of total energy consumed by the entire world.

World wind energy generating capacity by all the present firms is still much lower than the potential available.

Various Energy Sources Available

- **Conventional:** These include the fossil fuels like Coal, Oil, Gas, Hydroelectric and Nuclear energy are conventional energy resources.
- **Non–Conventional:** While fossil fuels will be the main fuels for thermal power plant there is an understanding that fossil fuels will get exhausted eventually in the coming century or so. Therefore other systems based on non-Conventional and renewable sources are being tried very much by many countries. The harmless Energy sources are Direct use of Solar energy, Wind energy, Ocean wave energy, Ocean Tidal energy, Ocean Thermal Energy, Geothermal energy and the other Biomass energy sources are the non-conventional energy sources already known.

Why to Choose Green Energy Source?

Energy sources which are not adding any additional pollution can be called as green energy sources. For example a wind farm of 1MW capacity saves approximately 200kN of coal which will be otherwise burned annually in a thermal power plant so also a wind turbine of 1MW capacity avoids emission of pollutant gases which are: 1. Sulfur dioxide 2. Nitrogen dioxide 3. Carbon dioxide 4. Particulates like fly ash.[1]

How Extracting Energy From Wind is Harmless?

Wind is air in motion. Mostly air in motion arises due to Solar Rays. Thermal gradient and the resulting pressure gradient on a global basis due solar rays received by the Earth is one of the major causes for air circulation. One primary force causing surface winds from the poles toward the equator of earth is convective circulation. Solar radiation heats the air near the equator much more and the density of heated air becomes lower and hence moves up from the surface of the Earth. Then at the surface it is replaced by cooler and denser higher pressure air flowing from the poles where naturally incident solar radiation is much lower. In the upper atmosphere denser higher pressure cold air is flowing down and keeps circulating from the poles. Where as in the upper atmosphere near the equator the air thus tend to flow back toward the poles and move away from the equator to avoid any possible vacuum. Hence the net result is global convective circulation with surface winds from north to south in northern hemisphere of Earth.

Local Wind

Local winds are caused by two mechanisms. The first is differential heating of land and water incident solar radiation during the day is readily converted to sensible energy of land surface and partly absorbed in layers below the water surface in sea and ocean and partly consumed in evaporating some of that water.

The land mass during day time becomes hotter than the sea and ocean water, which causes the air above the land to get heated up and become warmer than the air above water.

The warmer and hence lighter air by its density above the heated land surface rises up, and gives space for the cooler heavier air above the sea and ocean water surface moves over the land to replace the previous air over the land. This is the mechanism of shore breeze.

However at the night time the direction of the above breeze is getting reversed because the land mass cools down by radiating the heat into the sky more rapidly than the ocean / sea water by assuming a clear sky.

Another mechanism of local wind is caused by hills and mountain sides over the land. The air above the slopes of mountain heats up during the day and cools down at night more rapidly than air above the lower level lands and this causes the heated air in the day time to raise up along the slopes and relatively cooler and heavier air by its bulk density flows down the slopes at night time. This cycle is repeating every day and night.

Wind Generation is Little More Complex

- Earth's rotation causes a force resulting in an easterly wind velocity component in the northern hemisphere. Air particles are dragged along the rotation of earth due to gravitational attraction.

- Boundary layer frictional effects between the moving air and the earth's rough surface like mountains, trees, buildings and other similar obstructions.

2% of solar radiation falling on the face of earth is converted in to kinetic energy of wind. 30% of this is occurring in lower elevation of earth's atmosphere.

Wind Turbines

A wind turbine is a rotating machine which extracts kinetic energy of wind into mechanical energy. If mechanical this energy is used by machinery, such as for pumping water or for grinding wheat and other grains then the machine is

called a wind mill. If mechanical kinetic energy is instead converted into electricity, the machine is called a wind generator, wind turbine, wind power unit (WPU), wind energy converter (WEC), or Aero-Generator.

A Wind Turbine extracts energy from moving air by slowing the down the wind, and transferring this harnessed energy into a spinning Shaft, which usually turns an alternator or generator to produce electricity.

Extracting the Diffused Energy from Wind Flow

Three parameters are involved in extracting energy from the wind and they are: 1. Wind speed 2. Cross section of wind rotor which is known as swept area of rotor 3. Conversion efficiency of the Rotor, Transmission Efficiency of Gear system and Efficiency of Electrical Generator. [2]

It is not practically possible to extract all of the energy from the wind because to achieve this the wind will have to be brought to a complete halt and this in turn would prevent the passage of incoming air further entering through the wind turbine. A 100% efficient aero generator is not there and it would be therefore only be able to convert up to a maximum of a 59% of available energy in the wind into mechanical energy as per the Bet's derivation.

Kinetic Energy Contained in Wind

Energy available in wind is all kinetic energy. Kinetic energy of any particle is equal to one half of its mass (M) times the square of its velocity (V): $P_a = (\frac{1}{2} \times M \times V^2)$ ----------(1)

The amount of air passing through the wind turbine in unit time through a cross sectional area (A) with a velocity (V) is $A \times V$ and it is this mass (M) is equal to its volume flow rate multiplied by the density (ρ) of air which is estimated as 1.225 Kg/m³ at sea level.

$$M = \rho \times A \times V \text{ ----- (2)} \qquad P_a = \frac{1}{2} \times \rho \times A \times v \times v^2 \qquad \text{------- (3)}$$

$$P_a = \frac{1}{2} \times \rho \times A \times v^3 \text{ Watts} \qquad \text{------- (4)}$$

Available wind energy is proportional to cube of the wind speed. and it is the evident that a small increase in speed can have a marked effect on the power in the wind. Wind power is also proportional to air density (1.225 kg /m³at the sea level)

Maximum Possible Power Production from Wind

Cross section area of a rotating circular wind rotor $A = (\pi /4) \times D^2$ unit for area is m²

The wind power is proportional to this intercept area, thus an aero turbine with a large swept area has higher power produced than a smaller area machine.

Area is normally circular area where (D) is the diameter in a horizontal axis of machine so

Available wind power $P_a = \frac{1}{2} \times \rho \times \frac{\pi}{4} \times d^2 \times v^3$ in watts.   ------- (5)

This indicates that the maximum power available from the wind varies according to the square of the diameter of the wind area or square of rotor diameter. Thus doubling of the diameter of the rotor will result in fourfold increase in the available power. Wind machine intended for generating substantial amount of power should have larger rotors and be located in areas of high wind speed.

Actual Power Produced by Wind Turbine

$P = 0.5 \times \rho \times A \times V^3 \times C_p \times N_g \times N_b$ ------------ (6)

Where P = Power in watts (746Watts=1hp) (1000Watts=1kilowatt)

ρ = Air Density (1.225 kg/m³ at sea level, lesser at higher altitudes)

A= Rotor Swept Area / Area of Rotor Exposed to wind (m²)

C_p = Power Coefficient 0.59{Betz's limit}is maximum theoretically possible energy extraction limit if it is 0.35 and above it is a good design and there are better designs.

V = Wind speed in meter per second. N_g = Generator Efficiency (80% or possibly little more for a permanent magnet generator or grid –connected induction generator)

N_b= Gearbox / Gear Transmission and Bearing Efficiency could be around 95% each)

Present Study

The present study is under taken to investigate the working performance by power output and efficiency of energy conversion for horizontal axis wind turbine and to find out any possible improvement in energy conversion. Physical models of the horizontal axis wind turbine and a vertical axis wind turbine are placed in front of a constant air flow source, a fan and tested for their performance. Various experiments are conducted using ten different models of wind rotors by varying the solidity ratio and angle of the blades. Then with some of the rotors tests are conducted by arranging the blades such that the broader end of the blades at its tip and as well as at its root. Conventional design with the present new changes in the geometry of the wind rotors leads to a better engineering design of the horizontal axis wind turbine.

Numerical Calculations Involving Theoretical Efficiency

By doing Integration between a cut in velocity of 5 m/s to cut out velocity of 25 m/s velocity of wind / moving Air as Per Fluid Dynamics the Estimated Wasted Power and Estimated Useful Power for each of the Model Physical Rotors are given here:

The following equation for both Estimated Useful Power and Estimated Power Loss is the same with only the angle of the respective blade changing:

$P = \{(\rho \times A \times V^2 \times \sin\theta \times R \times 2 \times \pi \times N) / 60\}$ ---------------------(7)

$= [\{(\rho) \times (\int A) \times (\int V^2) \times (\int \sin\theta \times (\int R) \times (2\pi N)\} / 60]$

Useful power $= \{(\rho \times \pi \times \int_{r_1}^{r_2} r^2 \times \int_{v_1}^{v_2} v^2 \times \int_{\emptyset_1}^{\emptyset_2} \sin\theta \times \int_0^R R \times 2\pi N) / 60\}$ ------------ (8)

Wasted Power $= \{(\rho \times \pi \times \int_{r_1}^{r_2} r^2 \times \int_{v_1}^{v_2} v^2 \times \int_{\emptyset_1}^{\emptyset_2} \sin(90-\theta) \times \int_0^R R \times 2\pi N) / 60\}$ ---------- (9)

Total Power = Useful power + Wasted Power

Numerical Efficiency of Power Conversion = {(Useful power / Total Power) $\times$ 100} ---------- (10)

Where the individual parameters are in their respective appropriate units

'P' Power in *Watts*

'ρ' density of air, kg / m³

'A' is the swept area of the respective rotor, m²

'V' is the incoming velocity of wind, m / sec

'θ' is the angle of the respective blades, degrees

'R' is the effective radius in m at which the force due to the wind is considered to be acting to turn or rotate the rotor about its axis of rotation and

N is the number of rotations of the respective rotor per minute.

Table 1

Rotor No:	Useful Power (Watts)	Wasted Power (Watts)	Efficiency (%)
1	60.9	8.55	87.6
2	10.37	22.23	31.8
3	65.38	9.25	87.6
4	10.3	2.26	82
5	4.43	4.43	50
6	1.35	2.12	38.9
7	4.84	0.68	87.67
8	1.25	0.158	87.94
9	9.09	1.27	87.6
10	2.55	5.11	33.28

By Integrating between for example 0 m/s to 9 m/s for varying velocity of actual wind / moving Air as Per Fluid Dynamics the Estimated Wasted Power and Estimated Useful Power for each of the Model Physical Rotors are recorded.

The following equation for both Numerically Estimated Useful Power and Numerically Estimated Wasted Power is the same with only the change in the angle of the respective blade assembly.

These integrated values in Table 1 is the efficiency for the respective rotors which only represents the maximum efficiency by which the geometry of each of the model physical rotors are to be working with. Aero dynamic and frictional losses are not accounted in the above numerical study. If these losses are included then the actual efficiency can be obtained which may be closer to the experimental values.

Frictional Loss: For Rotor: 8 (Sample)

Dynamic viscosity of air (μ) =0.00093 Pa-sec

Friction factor (f) $=\dfrac{64 \times \mu}{\rho \times v \times d}$

$=\dfrac{64 \times 0.00093}{1.2 \times 9 \times 0.21}$

=0.02624

Head loss $=\dfrac{4 \times f \times L \times v^2}{2 \times g \times d} = \dfrac{4 \times 0.02624 \times 1 \times 9 \times 9}{2 \times 9.81 \times 0.21} = 2.063\text{m}$

Pressure=ρ ✕ g ✕ h

$=1.2 \times 9.81 \times 2.063 = 24.29$ N/m²

Force F $= pressure \times Area$

$=24.29 \times \frac{\pi}{4}(D^2 - d^2)$

D is the outer diameter of that rotor and d is the inner diameter of the same rotor.

F = 24.29×0.78(.105²-0.0075²) =0.2078 N

Torque = force per blade multiplied by radius of gyration which is 0.036 m multiplied by number of rotor blades for rotor number 8 which is 2 hence

F = 0.2078 × 0.036 × 2 N-m

Power $=\frac{(2\pi \times N \times T)}{60}$

N is the maximum r/min recorded for that particular rotor which is 1150

$=\frac{2\pi}{60} \times 1150.5 \times 0.2078 \times 0.036 \times 2$

$=1.79$ *watts.*

Experimental Study

For the qualitative and quantitative experimental study a Non Contact Tachometer is chosen to measure the maximum speed of the freely running rotors, a weighing machine and a measuring tape are used to measure the mass of the rotor and the geometry of the rotors. The maximum speed of rotation of the various rotors in r/min are recorded when they are placed in front of the fan and while the rotors are running freely with its own self weight alone in a ball bearing support. The fan is a source of constant velocity air flow. The kinetic energy possessed by the running rotors and the input energy by the air flow and hence the efficiency of energy conversion are calculated with the help of suitable equations.

Power P = {(2π N T) / 60}. For the torque T developed for a constant air flow or wind velocity and Power P can be calculated by measuring the speed of each of the rotors in rpm by the attached non contact type tachometer. These values are the one which are actually representing the actual physical performance of the respective rotors.

After calculating the efficiency of energy conversion from the energy input by the incoming air flow and the output energy of the various rotors which has different sizes, shapes, masses of nine horizontal axis physical models and one vertical axis physical models are presented in tabular forms for sample comparison.

Experimentally Measured Efficiency and other parameters for six of the Physical Model Rotors are presented as a sample:

Input Energy, Out Put Energy and Efficiency based on Energy extraction of each of the sample six model rotors from a constant velocity of Air Flow from a fan having a wind speed of 9 m/s is experimentally studied and further verified by repeated tests and they are presented in Table 2 and Table 3.

Table 2

Rotor Parameters	Rotor1	Rotor2	Rotor3	Rotor4	Rotor5	Rotor6	Error (%)
Weight(Kg-m/s^2)	18.41	23.20	5.91	2.86	5.189	0.156	±1
Mass(kg)	1.876	2.364	0.602	0.292	0.528	0.016	±1
Rotor speed (r/min)	470.5	157	800	1014	300	1312.5	±2
Rotor Blade Angle (degrees)	8	65	9	9	45	11 to 50	±0.5
Effective Radius (m)	0.275	0.29	.5	.16	.19	.125	±1
Solidity Ratio	0.73	0.58	0.441	0.441	0.522	0.105	
Kinetic Energy (watts)	46.56	7.3	33.68	5.43	2.39	0.80	±2
Power (watts per unit time)	94.041	104.3	83	17.08	47.23	32.71	±2
Efficiency %	49.4	7	38.17	31.7	2.39	2.44	±2
Wind velocity (m/s)	6.5	6.5	6.5	6.5	6.5	6.5	±2
Tip speed ratio	1.5	0.53	2.32	1.90	0.66	1.90	

The following equation is used to calculate the kinetic energy of the Running Physical models of the air / wind rotor: Kinetic Energy K.E = $(1/2) \times m \times k^2 \times \{(\pi \times D \times N) / 60\}^2$ ------(11)

Where m is the mass of the rotor, k is the radius of gyration in meter, D is the diameter of any particular rotor under consideration in meter, N is the maximum speed of rotation of that particular rotor in rotations per minute.

Table 3

Rotor No:	Input Power in Air (Watts)	Out Put Energy/Sec (Watts) With Comments	Experimental Efficiency in (%)
1	94.04 Horizontal axis	46.56 Optimum in all	49.40
2	104.43 Horizontal axis	7.30 Wrong blade angle	7.01
3	83 Horizontal axis	31.68 Only Three blades	38.17
4	35.86 Horizontal axis	11.36 Wrong blade size	31.68
5	47.23 Horizontal axis	2.39 Wrong Blade angle	5.07
6	32.71 Horizontal axis	0.80 Lot of Energy Wastage	2.44
7	24.79 Horizontal axis	2.17 Equal Blade Width	8.74
8	16.43 Horizontal axis	0.69 Waste of Material	4.24
9	35.56 Horizontal axis	12.2 Heavy but efficient	33.7
10	14.56 Vertical axis type	2.30 Usual Result	15

Figure 1: Sample of Model Test Rotors

Conseptual Conclusions of Present Experimental Study

- The experimental study is only a qualitative study. In the Existing Commercial Wind Rotors it is this solidity ratio at the outer periphery is very much lower. In fact one can observe the Tip width of almost all commercial wind rotor blades are smaller than the width at their root. Hence the energy harnessed by those working rotors are much lower than the potential available because of lower turning moments produced by these individual smaller tip rotor blades.

- If the tip width of the blades are much smaller than the required width then more will be the wastage that is the blowing air will escape through the annular gap in between the rotating blades without effectively transferring the kinetic energy of air to the rotor blades. To harness more energy from the passing wind a wider tip for all the three blades is necessary as otherwise the kinetic energy possessed by the wind is only wasted. Almost all the existing commercial wind turbines are working possibly only with a Lower Efficiency.

- Blade angle, Solidity Ratio and the Overall strength and Geometry of the blades needs to be redesigned for an optimum value to harness a possible maximum kinetic energy from the blowing wind is the deduction from the present work.

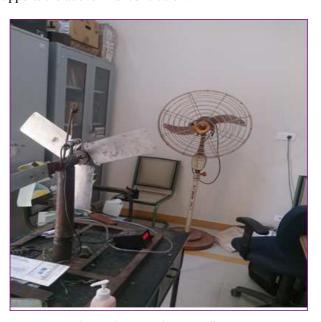   The test results firmly supports the above final conclusion.

Figure 2: Experimental Set up

- Wind energy is a perennial source of energy and also it is forever. That is as long as Sun rays are falling on Earth, wind will be here blowing. This study is very useful and it deserves its importance in wind energy usage.

- The Commercial wind turbine manufacturers all over the world may have to confidently change the existing design and incorporate this new finding in their wind turbines. By doing so they can become a pioneer and a successful leader in this large global Wind Turbine Business.

Figure 3: A Commercial Wind Turbine with Rotor Blades Having only Smaller Tips

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